Energy Harvesting Using Piezoelectric Elements to Power Microelectronic Devices

Synopsis submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

By

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JUNE, 2016

INTRODUCTION

Energy harvesting, also known variously as ambient energy harvesting or energy scavenging, is the conversion of energy extracted from ambient sources to useful forms like electricity and it's storage for use in the operation of wireless autonomous devices like wearable electronics, wireless sensor nodes, etc. The ambient sources of energy include the sun, wind, tidal waves, geothermal energy, vibrations, human motion, electromagnetic sources, etc [1]. A lot of energy seems to be wasted or rather dissipated in our daily activities when we move around, when we operate machines and also from our physiological processes like breathing, body heat, etc. Nature itself is an infinite source of great perturbations.

The sources of energy harvesting fall into two categories – natural and anthropogenic (man-made). Natural sources include solar, wind, tidal, geothermal energy, etc. Anthropogenic sources are mostly vibration sources encountered in and around machines, man-made structures like buildings, bridges, etc., and human physiological processes like walking, breathing, blood circulation, etc. Vibrations are the second most abundant source of ambient energy and as such can be used for harvesting useful amounts of energy which can power microelectronic devices. The most common methods of vibration energy harvesting exploited commercially or explored scientifically are piezoelectric, electromagnetic and electrostatic. Table 1 [2, 3] gives a comparison of these three methods based on their power density as well as their advantages and drawbacks.

Table 1. Commonly used methods of vibration energy harvesting

Method	Energy density (mJ/ cm^3)	Advantages	Disadvantages
Piezoelectric	35.4 [2, 3]	1. No need for external accruements 2. No start-up charge required 3. Can be fabricated in various shapes 4. Integrable into various structures	1. Low output currents 2. Overall performance and lifetime are limited 3. Brittle nature of material

Electromagnetic	24.8 [2, 3]	1. High output current 2. Variety of configurations and materials can be used	1.Low output voltage 2.Design problems due to poor magnet properties and limited number of turns of coil
Electrostatic	4 [2, 3]	1. Easily realizable in MEMS	1. Need initial charge 2. Low output current 3. High output voltages

Piezoelectric materials have been a popular choice for researchers in the area of energy harvesting for a few decades now. They have an inherent ability to convert mechanical energy into electrical energy. Piezoelectric elements can be deformed repeatedly to generate energy and power devices, with typical applications being sensors and industrial equipment [4]. A key advantage of these materials is that they can be optimised to suit specific applications using well established fabrication techniques. The present research work aims to study circular piezo-composite diaphragm elements as energy harvesters. These harvesters will be used as vibration energy scavengers as well as shoe based harvesters. Simulation and modelling of these harvesters will enable analysis of parameters which can't be studied in the physical model and help to optimize harvester design.

OUTLINE OF WORK

This work focuses on the investigation and development of generic energy harvesters using piezoelectric elements that are cost-effective, robust, easy to fabricate and easily integrable into different structures. Two ambient sources of energy are explored in the present research work viz. vibrating objects and shoes. First, different types of piezoelectric elements were analyzed to find a suitable one that could be used as an energy harvester and later energy storage circuits and its applications were analyzed.

Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress. This is the direct piezoelectric effect. In the converse piezoelectric effect, the material undergoes deformation in response to an applied electric

field. Piezoelectric materials exist as single crystal, polycrystalline as well as polymer materials. The important parameters that characterize these materials are their charge constants (*d*), voltage constants (*g*), coupling constants (*k*) and Curie temperature.

The uses of piezoelectric materials range from simple tools like a gas lighter to machining of materials (ultrasonic welding, bonding, drilling, etc.), for ultrasonic processors (e.g. to disperse liquid media), in the medical field (ultrasonic tartar removal, surgical instruments etc.) and also in sonar technology. Piezoelectric materials are also used in high resolution microscopes such as the Atomic Force Microscope.

The piezoelectric constitutive equations which relate the electrical and mechanical domains are given as:

$$T = c^E - eE \quad (1)$$

$$D = eS + \mathcal{E}^e E \quad (2)$$

where T is the stress (MPa), S is the strain, E is the electric field (V/m), D is the dielectric displacement (C/m^2), c^E is the elastic stiffness for constant E (MPa), e is the piezoelectric constant (C/m^2), $\mathcal{E}^e$ is the dielectric permittivity for constant strain (F/m).

OBJECTIVES OF THE THESIS WORK

In this work, our focus is on developing energy harvesters using piezoelectric materials. The following are the objectives of the present work

1. Development of piezoelectric energy generators.
2. Development of Energy harvesting and Power conditioning circuit.
3. Development of energy storage mechanism.
4. Interfacing integrated energy harvesting module to output application.

OBJECTIVE 1: DEVELOPMENT OF PIEZOELECTRIC ENERGY GENERATORS

Researchers have comprehensively reviewed energy harvesting using piezoelectric materials [5] with respect to different materials, efficiencies, ambient sources like vibrations, biomechanical sources, natural sources, machines, power harvesting electronics, etc. Sodano

[6] discusses power harvesting using different systems and their application to the real world. In Anton et. al [7], various shapes and configurations of piezo harvesters and factors affecting the power output are discussed. Mitcheson et. al. [8] reviews the principles and state-of-art in motion-driven miniature energy harvesters and discusses trends, suitable applications, and possible future developments. Goldfarb [9] analyses the efficiency of piezoelectric ceramics for electric power generation. Gambier & co. [10] discuss a hybrid energy harvesting system employing piezoelectric, solar and thermal generators.

Table 2 gives a comparison of the most commonly used piezo harvesters that were explored in this work. There are different types of piezoelectric elements available commercially like cantilevers, discs, diaphragms, rings, patches, etc. Although any piezoelectric material can act as an electromechanical generator, the choice of an energy harvester depends on the usable power that can be obtained and its suitability to serve the needs of a particular application.

Table 2. Most common piezoelectric elements used for energy harvesting

	Harvester type	**Power output level**	**Suitability**
	Cantilever [12 - 18]	1-2 mW	High frequency, low amplitude
	Diaphragms [19 - 25]	1- 30 mW	Wide range of frequency and amplitude

Piezoelectric rings, discs and patches are used as actuators and are not suitable for energy harvesting purposes. Piezoelectric cantilever energy harvesters have been a popular choice of researchers and commercial manufacturers and a lot of research has been carried out on these elements. Coated on a cantilever beam, piezoceramics allow simple energy harvesting without the need for additional mechanical structures. Relatively small external excitations result in output of several volts [11].The cantilever configuration offers large average strain in the piezoelectric material for a given applied force and low resonant frequencies can be achieved due to the low stiffness of the structure [3]. However, this configuration is not suitable for low frequency, high amplitude applications.

Piezocomposite diaphragm harvesters have been analyzed by researchers in various setups and excitation profiles. The circular structure is commonly used for sensors and actuators. Piezocomposite diaphragms consist of a metal substrate (commonly made of brass, steel or aluminium) on which a PZT disc is adhered. The composite structure can undergo large deformations as compared to a monolithic PZT disc which is brittle in nature. Due to their thin form factor and size, they can be incorporated into various structures [26, 27].

1.1 Selection criteria : The piezoelectric material used in the buzzer elements studied in the present research work is PZT-5H. Table 3 gives a comparison of the most commonly used piezoelectric materials [28].

Table 3. Properties of PZT 5H

Property	**PZT – 5H**	**PZT – 5A**	**$BaTiO_3$**	**PVDF**
d_{33} (pC/N)	593	374	149	33
d_{31} (pC/N)	-274	-171	-78	-23
k_{33}	0.75	0.71	0.48	0.15
k_{31}	0.39	0.31	0.21	0.12
Curie Temp. (^{0}C)	195	365	120	110

The criteria that determine the output power of a piezoelectric diaphragm are:

1. Ratio of thickness of piezo disc to metal substrate [h_p/h_m]
2. Ratio of radii of piezo disc and metal substrate [R_1/R_2]

Maximum energy is obtained for $h_p/h_m = 1.5$ and $R_1/R_2 = 0.72$ [29]. However, increasing the thickness of the piezo disc is equivalent to increasing the amount of piezo material in the element. This does increase the energy output but at the cost of increased bending resistance leading to reduced deflection and hence less energy.

Two different sizes of buzzer elements were used for the present work viz. 35 mm and 27 mm (standard sizes available commercially). From table 4 it is clear that the two sizes

selected have optimum values of h_p/h_m and R_1/R_2. The 40 mm buzzer was rejected due to its inability to withstand large impact forces (of the order of 100 N or more) without being permanently deformed.

Generally, an energy harvester extracts the maximum amount of power when operating at resonance. However in many cases, it becomes impractical to match the resonance frequency of the piezoelectric materials with the input frequency. Table 4 gives the dimensions of the diaphragm harvesters used in the present work.

Table 4. Dimensions of piezoelectric diaphragms used in the present work

Diameter of metal substrate (mm)	Diameter of piezo disc (mm)	Thickness of metal substrate (mm)	Thickness of piezo disc (mm)	h_p/h_m	R_1/R_2
27	20	0.20	0.20	1	0.74
35	25	0.25	0.25	1	0.71
40	25	0.19	0.19	1	0.63

1.2 Experimental testing of piezo buzzers (Higher frequency low amplitude) : The buzzer elements were analyzed using an impedance analyzer (Agilent 4294A Precision Impedance Analyzer) to determine their electrical properties like polarity, impedance and capacitance. Figure 1 shows the experimental setup used for vibration energy harvesting. Table 5 gives the results of the experimental analysis.

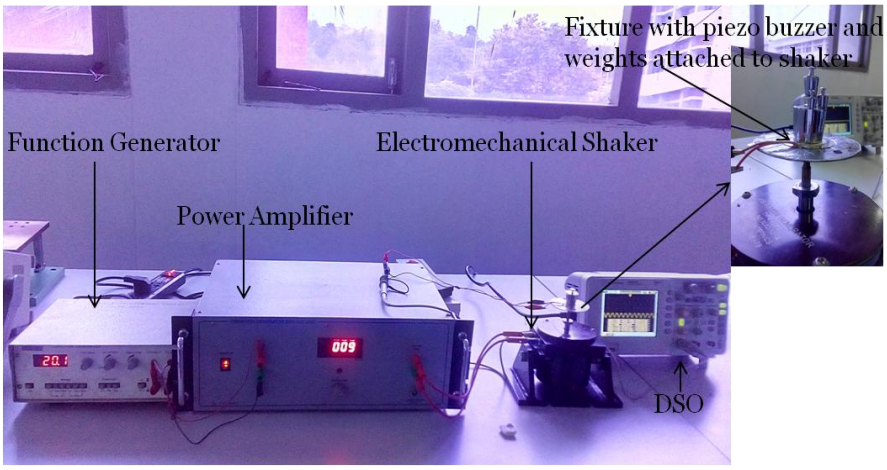


Figure 1. Experimental setup for vibration analysis of piezo buzzer

Table 5. Results of vibration analysis of piezo buzzers

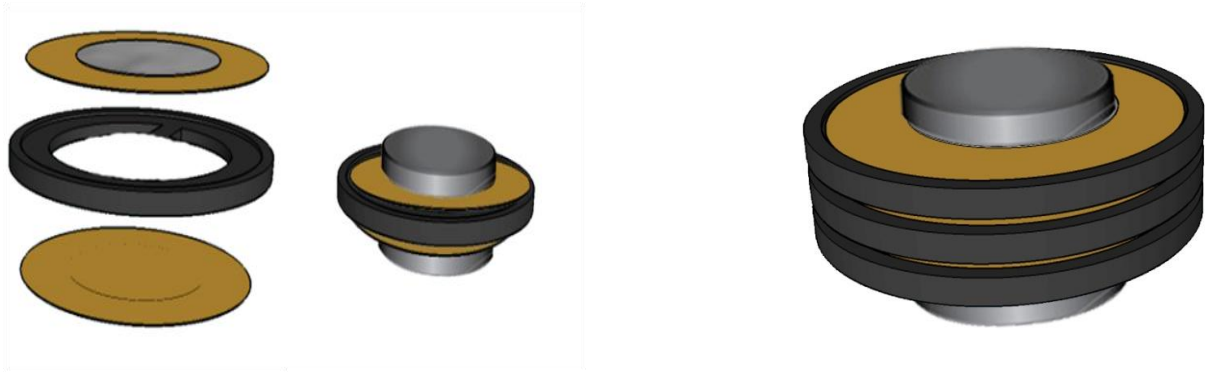
Buzzer size (mm)	V_{oc} without pre-stress (volts)	V_{oc} with pre-stress (volts)	Optimum pre-stress (gm)	Peak power (mW)	Optimum load resistance (kΩ)	f_r without pre-stress (Hz)	f_r with pre-stress (Hz)	Charging time of supercapacitor (min)
35	0.7	18	57	0.223	126	26.7	22.6	153
27	0.65	16	25	0.086	133	25.6	24.2	167

Clearly, the output voltages are very low without pre-stress. The output voltage increased dramatically after application of pre-stress. The output power of the 35 mm buzzer is greater than that of the 27 mm buzzer. Also, the resonance frequency was observed to decrease with the application of pre-stress. After a certain optimum value of the pre-stress, the output voltage decreases indicating that there is a limit to the extent up to which the voltage increases linearly with pre-stress.

The results show that piezo buzzer elements are capable of harvesting usable electrical energy even at low frequencies and accelerations.

1.3 Fabrication and bench testing of drum harvesters with footfall simulator

Fabrication of drum harvesters : Drum harvesters were fabricated using the piezo buzzer elements. Each drum harvester consists of a steel ring sandwiched between two piezo buzzers as shown in figure 2. Use of the steel ring enables utilization of the 31 mode. In order to obtain a large bending curvature and thus a large deflection normal to the face of the drum, the brass discs are clamped at the rims and specifically with large free area [30].



(a) **(b)**

Fig 2. (a) Drum harvesters and (b) Drum stack

Testing of drum harvesters with footfall simulator : There was a requirement to test the piezo generators under simulated conditions of footfalls. However, no standard bench testing instrument was available for simulating footfalls. A custom footfall simulator was designed for testing of the piezo generators. The simulator consisted of a solenoid driven mechanism with a hammer, a variac, a proximity sensor and displacement sensor. The arrangement was operated using a pre-programmed Arduino microcontroller board which enabled varying the impact frequency between 1 and 10 Hz.

Table 6. Power output v/s increasing number of drums

No. of drums	Power output (mW)	
	27 mm	35 mm
1	1.51	1.60
2	3.27	3.23
3	3.45	3.64
4	3.55	3.75

From Table 6, it can be inferred that as the number of drums increases, the power increases. But after adding 3 drum in the stack, there is very little increase in the power output. This may be due to the increased rigidity of the stack as more drums are added.

Table 7. Power output v/s impact frequency

Impact Frequency	Power output (mW)	
	27 mm	35 mm
1	3.73	3.42
2	4.51	5.35
3	4.68	6.71
4	4.79	7.08
5	4.93	7.30

Table 7 shows that increasing the impact frequency increases the power output for both the stacks. But the power saturates at about 5 Hz.

Table 8. Power output v/s number of stacks in shoe

Profile	Heel Power output (mW)		Forefoot Power output (mW)	
	1 Stack	2 Stacks	1 Stack	2 Stacks
Walk	3.86	6.27	3.20	5.59
Run	4.43	6.59	4.24	6.32

Table 8 gives the results of the power output in actual walking and running experiments with the stacks embedded in shoes. It is clear that the output power is greater for 2 stacks than for one stack embedded in the shoe. Also running produces more power as compared to walking.

1.4 Experimental Testing of drum harvesters under high frequency (~200 Hz) and low amplitude (0.5 N) conditions

Impedance analysis of the drum harvesters was carried out using an impedance analyzer (Agilent 4294A). Figure 3 shows the experimental setup for the drum harvesters for vibration energy harvesting.

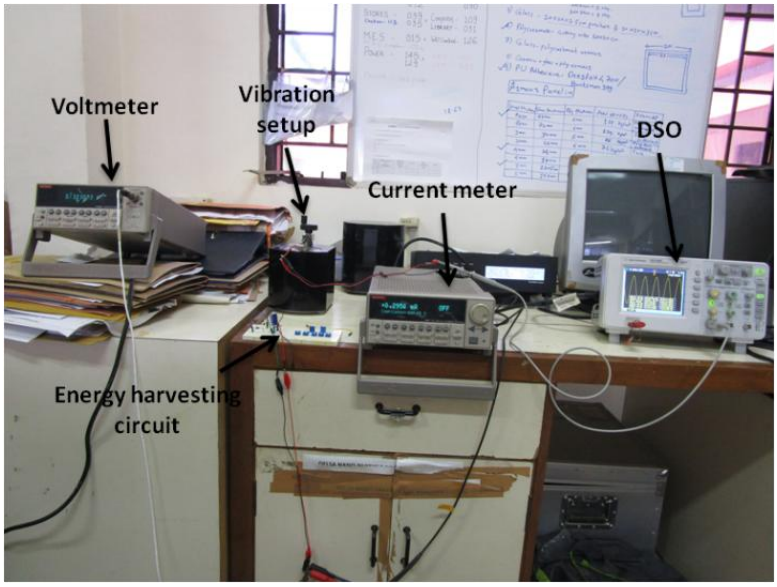


Figure 3. Experimental setup for vibration analysis of drum harvesters

The analysis was done with samples in triplicate that is 3 samples for each configuration. Table 9 gives the results of experimental analysis of drum harvesters.

Under vibrational excitation, the drum harvesters were able to charge a 0.1F/5.5V supercapacitor up to 5 volts.

The energy stored in the supercapacitor was $1/2CV^2$ = 1/2 x 0.1 F x 5 x 5 = 1.25 J. Thus, in the present work, we were able to achieve greater energy output (1.25 J in around 30 min) whereas in previous research [31], time taken to charge a supercapacitor to 5 V was 16 days which amounted to only 33.125 mJ of energy generated in one hour. The results show that useful amounts of power can be generated with vibration harvesting using drum harvesters even under very low amplitude excitation profiles.

Table 9. Results of vibration analysis of drum harvesters

Drum OD (mm)	Drum ID (mm)	Resonance Frequency (Hz)	V_{AC} (Experimental) (volts)	Peak Power (mW)	Charging time of supercapacitor (min)
35	31	205	29	1.932	26
35	**32**	**206**	**33.28**	**2.142**	**24**
35	33	210	29.34	1.918	28
27	23	210	37	2.259	26
27	**24**	**213**	**38.04**	**2.463**	**23**
27	25	219	35.9	2.384	35

OBJECTIVE 2: DEVELOPMENT OF ENERGY HARVESTING AND POWER CONDITIONING CIRCUIT

The piezoelectric drum harvesters generate high AC voltage, there was a need to design a suitable power conditioning circuit that could achieve the following goals:

- Conversion of high AC voltage (~150 - 200 V) to DC
- Stepping down high DC voltage (~60 V) to 5 V DC
- Obtaining regulated voltage output of 5 V DC

Standard interface circuit

Initially, to harvest energy from the piezo energy harvesters, a standard energy harvesting interface was used. Figure 4 gives the layout of the circuit which consists of a diode bridge rectifier and a filter –cum – storage capacitor.

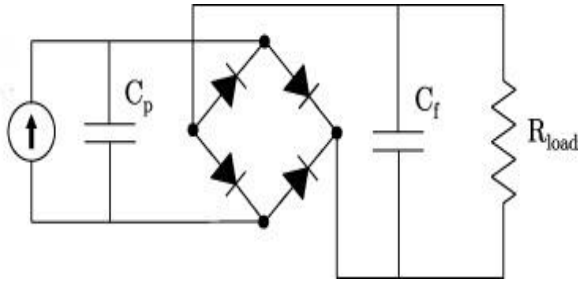
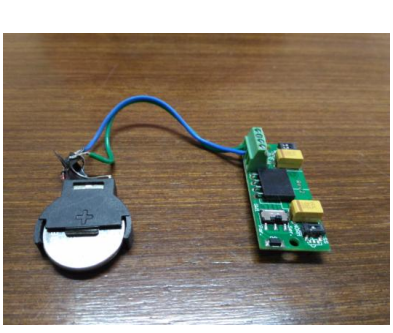


Figure 4. Standard energy harvesting interface.

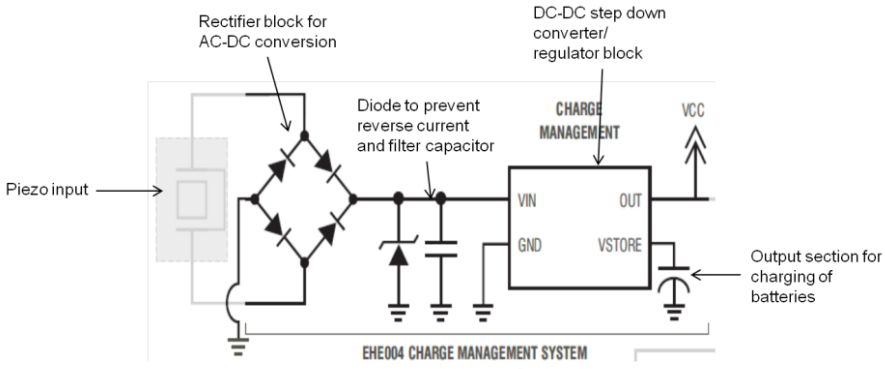
The above interface is simple to configure but suffers from several drawbacks. AC-DC conversion is achieved with this setup but there is no voltage regulation. Further, it is not suitable for directly powering microelectronic devices that run on low voltages (1-5 Volts).

The EHE 004 energy harvesting module

A commercially available energy harvesting circuit (EHE 004 by Volture Inc. USA) was used to overcome the above drawbacks (figure 5). This circuit was able to achieve AC-DC conversion, DC-DC step down of high voltage and was able to provide 3.6 V regulated DC output. However, the drawbacks of this circuit were that it was expensive, could give a maximum output voltage of only 3.6 V which was not suitable for devices running on 5 V and finally, the charging rate of batteries with this setup was very slow.



(a)



(b)

Figure 5. (a) EHE 004 energy harvesting circuit (b) Block diagram of EHE 004

LTC 3588 energy harvesting IC

To overcome these drawbacks we used a commercially available energy harvesting IC (LTC 3588 by Linear Technologies USA). Figure 6 shows the layout of the circuit.

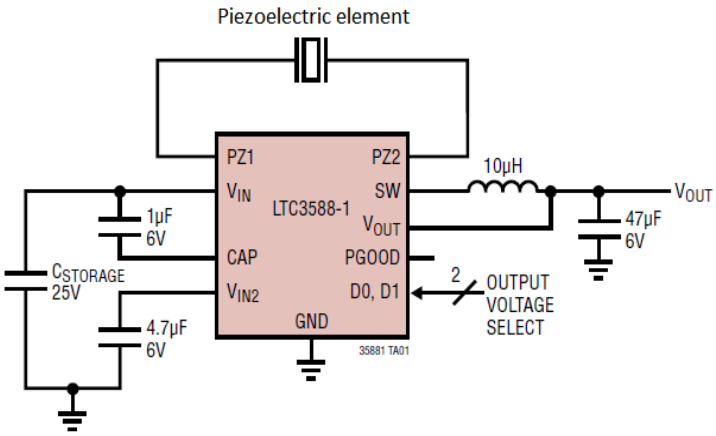


Figure 6. Energy harvesting circuit employing LTC 3588 IC.

The above circuit achieves rectification, down-conversion as well as regulation. It converts the high voltage output of the piezoelectric element to DC. It steps down the DC voltage which would otherwise be still too high for powering devices. Finally, it gives a regulated output voltage of either 3.6 or 5 volts as per the circuit configuration. The efficiency of this circuit is very high (~90%).

OBJECTIVE 3: DEVELOPMENT OF ENERGY STORAGE MECHANISM.

For energy storage, electrolytic capacitors, supercapacitors, Li-ion cells [32] and NiMH batteries [33] were tested. We were able to charge different electrolytic capacitors and supercapacitors (Cornell-Dubilier 5.5 V/ 0.1 F/ 0.33 F) with the shoe- based harvesters. A 0.1 F supercapacitor was charged up to 3.5 V while a 0.33 F supercapacitor was charged up to 2.5 V by walking for 2 hours. The harvesting circuit consisted of a standard interface with a schottky bridge rectifier, 5 V zener diode and the supercapacitor. Using the equation for energy stored in a capacitor, total energy = $1/2CV^2$ = 1/2 x 0.1 x 12.25 = 0.61 J and 1.03 J for the 0.1 F and 0.33 F supercapacitors respectively . To calculate the energy per step, we divide this energy by the number of steps. Energy per step = Total energy/3600 = 170.14 x 10^{-6} J and 286.11 x 10^{-6} J for the 0.1 and 0.33 supercapacitors respectively (at one step per second for 2 hours). A 3.6 V rechargeable lithium ion button cell was also charged similarly. The voltage developed in the cell after 2 hours was only 300 mV. This indicates that these

harvesters are not optimum for directly charging lithium ion cells. Table 10 summarizes the results of capacitor charging experiments.

Table 10. Charging of capacitors with energy harvesting shoes

Sr No	Capacitance	Value (Farad)/ Rating (volts)	Charging time (min) with walking	Voltage developed (volts)
1	Electrolytic	470u/63	5	20
2	Tantalum	100u/15	5	11
3	Tantalum	100u/16	5	11
4	Supercapacitor	0.10/5.5	5	0.20
5	Supercapacitor	0.33/5.5	5	0.15

The consistency of the output voltage over time was studied by having a subject walk in the shoes daily for a week. The peak output voltage (open circuit) was seen to reduce by about 30 %. However, thereafter, the output remained fairly constant and no significant drop in voltage output was observed over several months of testing. The deterioration in voltage output can be minimized by suitably reinforcing the embedded stacks and designing optimum insoles for the shoes. The stacks were found to be sensitive enough to generate usable power even with light foot tapping.

The charging rate of NiMH batteries of 3 different capacities (22 mAh, 70 mAh, 160 mAh/ 4.8 V) using the shoe harvesters was studied. A simple standard interface consisting of a schottky bridge rectifier and a large capacitor (4700μF) was used as the charging interface for this battery. The reason for using the standard interface circuit is that these batteries don't require voltage regulation [34]. Table 11 gives the results of the charging experiment.

Table 11. Charging of NiMH batteries with shoe based drum harvesters

Battery capacity	Initial voltage (volts)	Final voltage (volts)	Charging time @ 70 steps per minute (min)
4.8V/ 22mAh	1.49	4.42	30
4.8V/ 70mAh	1.89	4.01	40
4.8V/ 160mAh	2.39	3.70	27

To achieve a regulated output voltage, LTC 3588 energy harvesting IC was used. With both the shoes, the IC was able to give a regulated output of 3.6 volts after walking 4-5 steps. As an application, a RF transmitter was successfully powered with the shoe harvesters. The transmitter was able to transmit a code after every 4-5 steps.

Various researchers have reported shoe-based energy harvesters employing piezoelectric elements. Table 12 gives a comparison of such systems with the present work. Guzman [39] describes an application of piezoelectric stack in a floor stack energy harvesting device. By using a novel frame structure, the peak power obtained was 60 mW for a force of about 37 N.

Table 12. Shoe based Energy Harvesters

Inventor	Year	Output Power	Mechanism	Application
Shenck [35]	1998	1 -2 mW	Curved patch and flexible stave	RF encoder
Leinonen [36]	2012	0.162 mW	Moonie	Not demonstrated
Zhao [37]	2014	1 mW	PVDF sandwich structure	Simulated wireless transmitter
Fu [38]	2015	6 mW	Rotary magnetic generator driven by air pumped turbine system	Not demonstrated
Present research work	**-**	**8.06 mW**	**Stack Individual drums**	**Powering of RF transmitter**

OBJECTIVE 4: INTERFACING INTEGRATED ENERGY HARVESTING MODULE TO OUTPUT APPLICATION.

As an end application the inclusive energy harvesting system was interfaced with a RF transmitter that could transmit at a frequency of 434 MHz. The module was further modified so that it could be either self-powered (that is it could be powered by the energy harvester alone) or battery powered. Additionally, the battery can be charged using the energy harvesting system. Thus this is a self contained power harvesting system.

As an application for energy harvested from high frequency low amplitude vibration profile, a supercapacitor was successfully charged using the piezo buzzers and drum harvesters excited at their resonance frequencies as described in experiments in section 1.3 and section 1.6. The charged supercapacitor was used to power an Arduino microcontroller board which was pre-programmed to flash a LED. The microcontroller was able to run the program for about 10 seconds before it stopped as the voltage across the super capacitor fell below 3 V which is the minimum voltage required by the Arduino board**.**

CONCLUSION

Energy harvesting using ambient vibrations is a very practicable method and can be used for powering today's low power microelectronic devices. In the present research work, attempts were made initially to fabricate flexible piezoelectric material based energy harvesters which did not succeed. After screening of a variety of commercially available piezo harvesters, diaphragm harvesters were selected as the energy harvesting elements. Effect of pre-stress was studied experimentally and via simulation, and it was found that increasing the prestress increased the power output of the diaphragm harvesters, at the same time reducing the resonant frequency. Maximum power outputs of 223 μW and 86 μW for the 35 mm and 27 mm piezo elements were obtained respectively.

It was shown that increasing the steel ring ID increases deformation in the structure which leads to higher output power in drum harvesters. In the experimental analysis, the optimum steel ring IDs were 32 mm giving an output power of 2.463 mW and 24 mm giving an output power of 2.142 mW for the 35 mm and 27 mm piezo elements respectively. A supercapacitor was charged to 5 volts using the energy harvesters and was used to power a microcontroller. Bench testing of drum stacks using a footfall simulator gave a maximum power output of 7.3 mW with impact frequency of 5Hz and maximum power of 6.59 mW was achieved with a running profile with two drum stacks.

Experimental results have so far shown that power levels in the hundreds of microwatts to a few milliwatts can be achieved using diaphragm and drum harvesters.. Though the instantaneous power output is quite low, it can be used to charge a suitable energy storage device like a supercapacitor or rechargeable cells or batteries over a longer period of time. it was demonstrated that a supercapacitor charged up to 5 volts with drum harvesters was able to power a Arduino microcontroller board. Also, NiMH batteries of different capacities were charged successfully. A RF transmitter was also powered with the shoe harvesters. Other applications that can be proposed are as follows:

a. Powering of a low power GPS module for location detection.
b. Powering a low power transceiver module for short duration SOS communication like transmission of a distress signal.
c. Powering of wireless sensor nodes installed in remote locations using ambient vibration as the source.

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